

No 'cut off' in the High Energy Cosmic Ray Energy Spectrum

Tadeusz Wibig

*Experimental Physics Dept., University of Łódź and
The Andrzej Soltan Institute For Nuclear Studies, Cosmic Ray Lab.,
Łódź, Uniwersytecka 5, POB 447, Łódź 1; Poland*

Arnold W. Wolfendale

Physics Department, University of Durham, Durham, UK.

It is often claimed that there should be a 'GZK cut-off' in the flux of extragalactic cosmic rays, arising from interactions between the cosmic rays and the cosmic micro-wave background photons (e.g. [1] and [2]). Some experiments ([3] and [4]) show particles of even higher energy than this value and this has led to claims for exotic processes (e.g. [5] and [6]).

We contend that such claims are unnecessary - there is no predicted cut-off, rather a continuation of the injection spectrum at reduced intensity. We have combined the world's data and shown that the prediction for a rather flat injection spectrum (exponent: 1.9 - 2.2) in the case of universal particle injection provides a reasonable fit to the data. Conventional forms for the particle attenuation in the intergalactic medium (e.g. [7] and [8]) have been assumed. Either protons or iron nuclei (or a mixture) will suffice.

Attention is drawn to another aspect, too, that of the losses on the infra-red radiation which may be intense near to strong sources and for sources in galaxy clusters. The attendant magnetic fields near the sources leads to significantly long diffusion times through the strong infra-red fields. Two 'case histories' are considered.

The question of the origin of cosmic rays in general is a difficult one, that of those of the highest energies (known to mankind) is singularly so. Here, we examine the situation above about 10^{18} eV (the spectrum extends to beyond 10^{20} eV) in the light of very recent knowledge. Our aims are three fold: to correct misapprehension about the so-called 'Greisen-Zatsepin-Kuzmin cut-off', to consider the evidence for a transition from Galactic (G) to extragalactic (EG) origin near 10^{19} eV and to stress the need to consider the strong infra-red background radiation (IRB) near very strong sources (such as quasars) and sources in galaxy clusters, which are often considered as prime candidates for ultra-high-energy cosmic ray sources (UHECR).

Following our earlier work (Ref.[9]) we have updated our combination of the world's data. We find that by normalizing energies and intensities to the position of the minimum in the (usual) plot of $\log E^3 \times I(E)$ vs. $\log E$ we are able to secure a reasonably consistent set of data from the 6 sets of results considered (the arrays at Volcano Ranch, Haverah Park, AGASA, (& AKENO), Yakutsk, Hi-Res and Fly's Eye - see [9] for references) up to about 3×10^{19} eV. At higher energies there is a significant disparity between measurements, with conventional terrestrial particle arrays, typified by AKENO, and those involving use of the Cherenkov or Fluorescence technique, typified by the 'Hi-Res' array. The displacements in energy involved are typically 0.2 in $\log E$, i.e. not much higher than the random errors.

We proceed in alternative directions. The first case (Figure 1(a)) assumes that the Hi-Res data have accurate energy and intensity calibrations; the second case - which can be regarded as an upper limit in energy calibration - assumes that the AGASA calibration is correct (Figure 1(b)).

Several observations can be made about the Figures, as follows:

- (i) The data below $\log E = 19.5$ (Case (a)) and 19.8 (Case (b)) show an excellent fit to the sum of two components: G (Galactic) and EG (extragalactic). G falls with increasing energy because of a lack of sufficiently energetic sources and a lack of magnetic trapping. (see Ref.[10]) and the EG spectrum initially is a power law before losses on the CMB set in. We would expect, a priori, that the EG spectrum would have an exponent in the region 1.8 to 2.4, this being the injection spectrum expected for Fermi-style acceleration. Some explanation of the range is necessary, as follows. It has been shown that the standard value of 2.0 is not necessarily the minimum value - harder spectra can be generated by the first order mechanism in shocks propagating into plasmas with low beta values [11]. Softer spectra, i.e. exponents bigger than 2.0 appear where losses are important during the acceleration process. It is well known that below $\log E = 15$, Galactic sources have an injection spectrum in this region - the steeper spectrum observed at low energies is because of the energy-dependent Galactic trapping caused by an energy-dependent diffusion coefficient for escape. We regard the excellence of the fit of the points to the sum of G and EG as a strong indication that the transition from G to EG occurs here ($\log E = 18.7$ case (a), 18.9 case (b)). We find no support for the arguments [12] favouring a transition at a much lower energy ($\log E = 17.4$ - a factor 20 lower in energy). It would be difficult to achieve such a sharp 'ankle' if all the

particles in the region were extragalactic.

The Extragalactic energy density for our case (a) is 10^{-6} eV cm $^{-3}$.

- (ii) Fits have been made for commonly considered cases, where the sources are distributed smoothly throughout the universe, with one proviso - we take 6 Mpc as the minimum distance to a source. The reason for this proviso is that closer sources would almost certainly be seen as such. We [14] claimed some years ago a tentative sighting of a nearby pair of colliding galaxies at 7 Mpc. The claim has not (yet) been confirmed but colliding galaxies are still considered a possible mechanism for UHECR origin. Insofar as the mean density of 'normal' galaxies is about 3×10^{-2} Mpc $^{-3}$, the number of galaxies within a radius of 6 Mpc is ~ 9 , including our own.

The whole philosophy of considering 'normal' galaxies is to imagine that they contain Galaxy-like sources which extend to more than 10^{20} eV but that, by chance, our Galaxy does not contain one, or more, at the present time [13]. More specifically, UHECR from Galactic sources are not arriving at the present time.

- (iii) The prediction of Ref.[1], denoted 'T' in Fig 1 (b), which shows a rapid monotonic 'cut-off' has been much quoted and, indeed, used as a claim for new physics for the case where particles are observed above 10^{20} eV. We consider this steep line to be inappropriate.
- (iv) Our prediction using standard attenuation factors for interactions with the radiation fields (principally the CMB) present universally, are shown in each case.

Insofar as we normalize the attenuation factors at $\log E = 19$ there is not much difference between the predicted spectra for proton - and iron - primaries. There will be some difference at lower energies but uncertainties in the shape of the Galactic spectrum allow these differences to be compensated.

It is evident that if the injection spectrum is flat enough (differential exponent $\gamma = 2.2$ for case (a) and 1.9 for case (b)) a tolerable fit can be achieved to the data. The peak in case (a) can perhaps be accounted for in terms of a stronger than average infra-red background (IRB) near the sources; this topic is taken up in more detail later.

What is certain at this stage is that there is no 'GZK cut-off' expected, for physically reasonable injection spectra. It can be added, in parenthesis, that the term 'cut-off' was a mis-translation from the original Russian (V.Kuzmin, private communication).

We turn now to EG 'systems' which are much stronger in radio, optical, X-rays and gamma rays than normal galaxies, these potential UHECR sources include active galactic nuclei (AGN), quasars, galaxy clusters and, as remarked already, colliding galaxies. Our particular concern is to draw attention to the fact that they will be surrounded by strong IR fields and regions of significant magnetic fields associated with low energy CR escaping from the AGN. Interestingly, the IRAS infra-red satellite showed [15] that many AGN sources were stronger in IR than in all other wavelengths and that colliding galaxies (mergers) are often associated with very strong infra-red emission. We can take a strong quasar as an example; with a luminosity LIRB $\sim 2 \times 10^{45}$ erg s $^{-1}$ and it produces an IRB of $\sim 5 \times 10^{-2}$ eV cm $^{-3}$ at a distance of 1 Mpc. There will be significant spectral distortion for particles (protons or nuclei) escaping from such a source due to interactions with the enhanced IRB. Concerning quasars, a problem appears concerning their distance. Whereas the range of a 2×10^{20} eV proton is ~ 55 Mpc against CMB interactions, most quasars are further afield. Particles of lower energy will not arrive either within the Hubble Time because of the magnetic field in the IGM (a few nG): the diffusion time is too long.

Distant quasars are important, however, if - as seems likely - they are an important source of UHECR in the Universe. The interaction of their particles with the CMB and the enhanced IRB will produce gamma rays and neutrinos which have the possibility of arrival and detection at earth. Calculations so far made may have underestimated the likely intensity of these secondary particles.

It is with perturbations to the spectral shape of UHECR from more local sources that we are more concerned here. Such sources are galaxies in general - see the previous discussion - AGN, colliding galaxies and galaxies in clusters. The effect of enhanced IRB in galaxies is negligible when averaged over all sources ($\sim 0.1\%$). That in colliding galaxies is more serious insofar as many of the most prominent IR emitters are, in fact, galaxies in collision [15]. Equally serious will be the situation for strong sources in galaxy clusters. The nearest cluster is VIRGO (at 15 Mpc) and this contains the celebrated AGN: M87. There is also the likelihood of strong shocks in clusters giving rise to UHECR.

Figure 2(a) gives an indication of the expected magnitude of the effect of losses (IR and CMB) on protons leaving a source surrounded by a magnetic field and IRB of its own making.

Figure 2(b) gives results for more modest sources in a cluster of galaxies. (AGN, shocks within the intercluster medium, etc.). Measurements have shown that many clusters have magnetic fields in the region of $5 \mu\text{G}$ [16] and calculations have been made with $B = 1 \mu\text{G}$ and $5 \mu\text{G}$. The IRB has been taken as in Figure 2(a), viz with the IRB energy density at $R = 0.3$ Mpc increasing by 100 (the IGM value) at $R = 3$ Mpc and higher closer in still. It is

evident that the reduction in the important energy region near 10^{19} eV can be large; this factor may lead to some suppression of the bump in figure 1 predicted for a uniform. EG source distribution, such as cluster-contained sources would be, in first order. Clearly, accurate calculations for specific source models will need to take losses by way of infra-red radiation seriously.

We conclude that there is no GZK 'cut-off' expected in the energy spectrum of UHECR if the injection spectrum is sufficiently flat and extends far enough in energy. The problem is 'how do UHECR get their extremely high energies in the first place' rather than 'how is it that such particles are able to reach us?' Concerning the effect of infra-red radiation losses, these can be serious for very strong sources and for strong sources in galaxy clusters containing significant magnetic fields.

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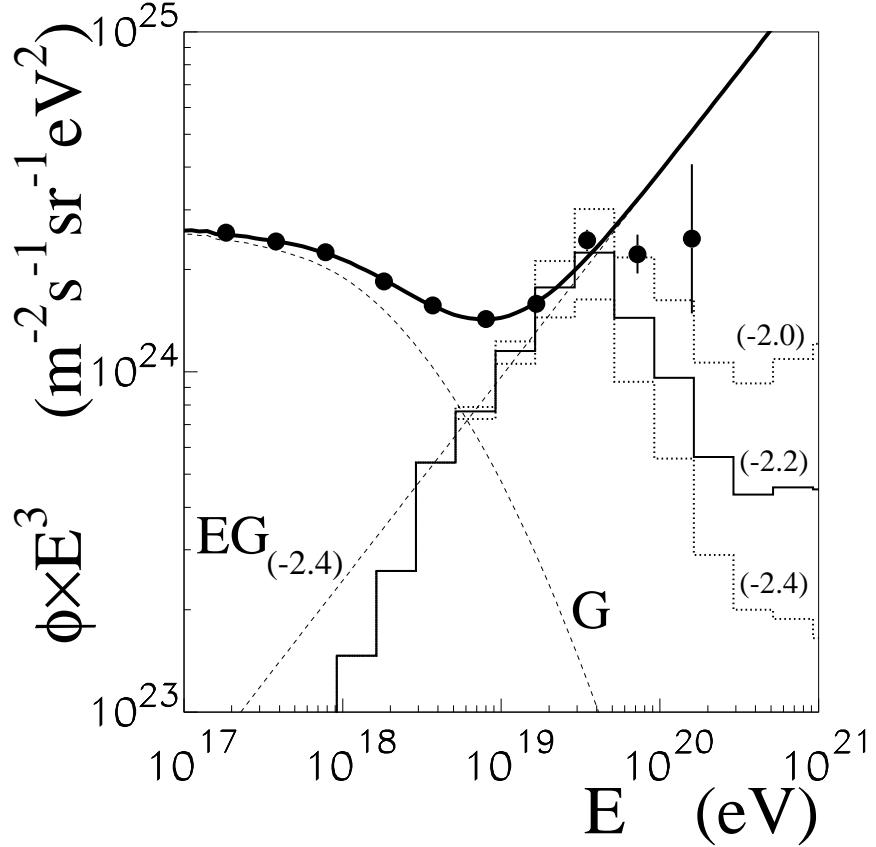


Figure 1a: Primary energy spectrum of ultra-high energy cosmic rays. The points represent the summary of the world's data after normalization to the same 'ankle' position and using the scale for the Hi-Res experiment [9]. The sharp minimum ('ankle') at $\log(E) \sim 18.7$ is regarded by us as strong evidence for a transition from Galactic (G) to Extragalactic (EG) particles; primary protons are assumed in the comparison of expectation with the points but the results for primary iron nuclei would be similar, in view of the normalization of the expectations to the EG line at 10^{19} eV.

The lines represent expectations for a universal distribution of sources beyond 6 Mpc (sources closer than this would have been recognized already). The numbers in brackets are the exponents of the injection spectra adopted in the calculations.

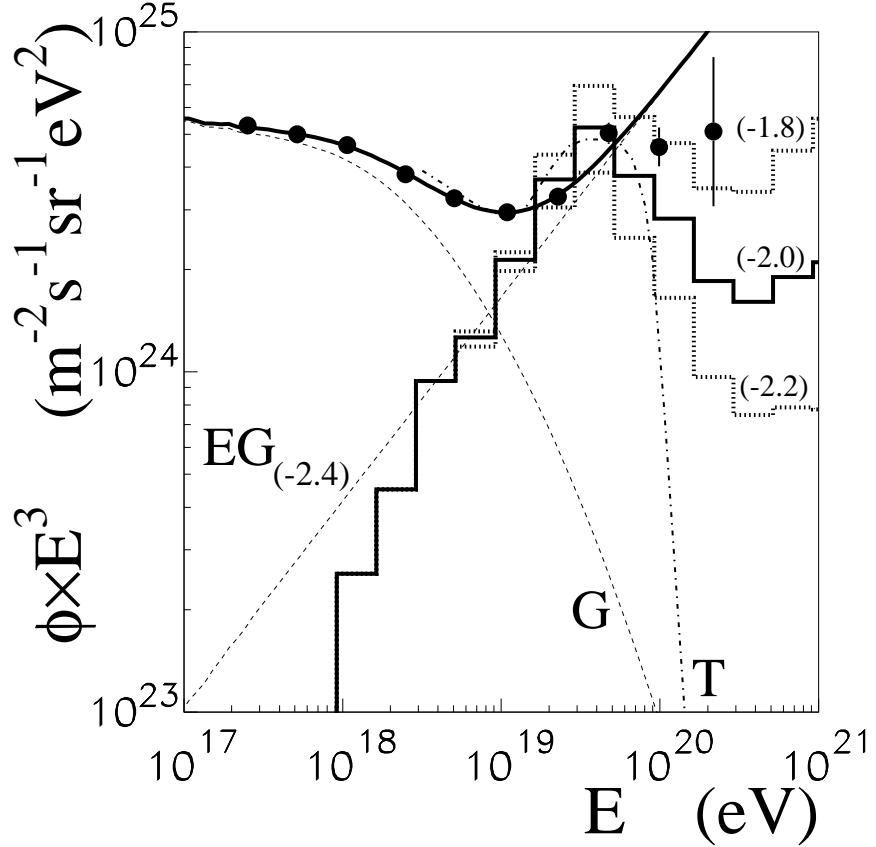


Figure 1b: As figure 1(a) but for the normalization of the experimental data to the intensity and energy determined in the AGASA experiment [9].

'T' denotes a prediction commonly quoted [1] but one which we regard as inappropriate; certainly, uniform UHECR injection with an energy - independent exponent would not give such a catastrophic fall.

It is evident that a GZK - 'cut-off' is neither observed nor predicted.

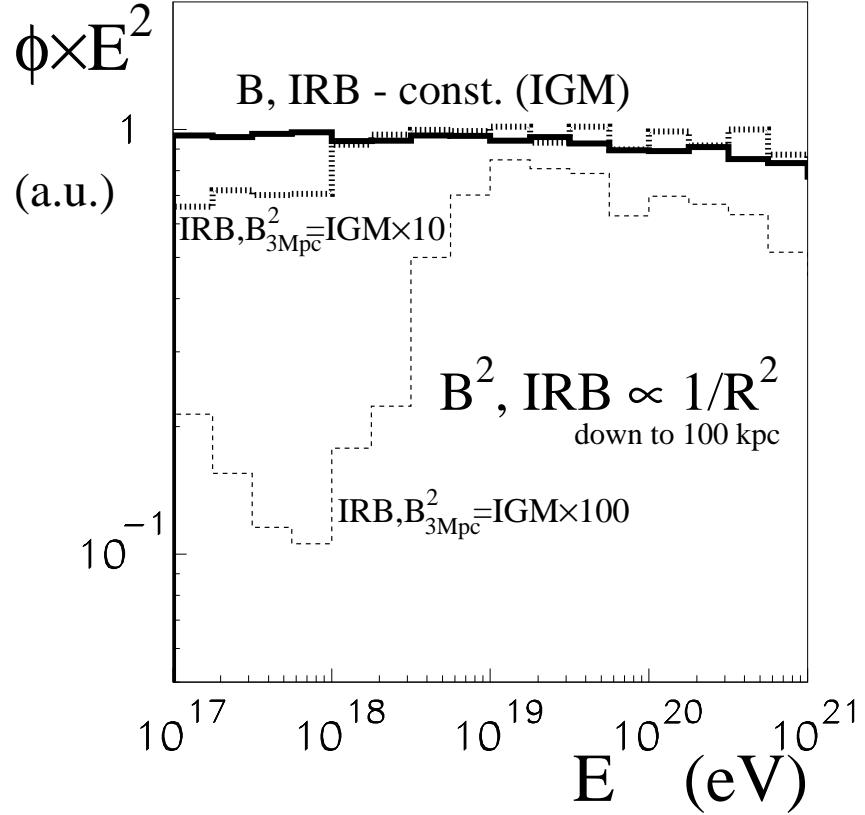


Figure 2a: UHECR spectra expected on emergence from a sphere of radius 3 Mpc round a very strong source. Various dependencies of the magnetic field, B, and infra-red intensity, IRB, on distance from the source have been assumed. Details are given on the graph. Injection spectrum of the form E^{-2} .

The actual spectra depend on the form of the cosmic ray diffusion; here we adopt the Kolmogorov formalism. In calculations for models assuming injection from strong sources the assumed injection spectrum should be multiplied by an appropriate function of the type shown, before propagation calculations commence.

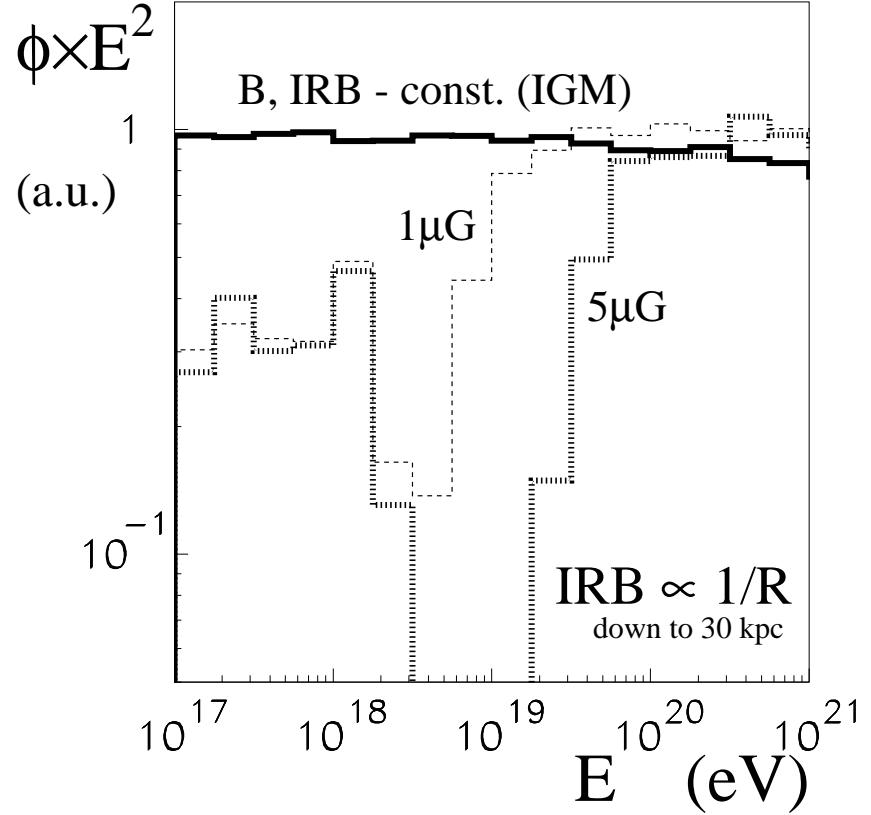


Figure 2b: As figure 2(a) but for the case where the magnetic field is constant over the cluster, of radius 3 Mpc. This field comes from emission from all the galaxies in the cluster. A value of $5\ \mu\text{G}$ is representative of a rich cluster.